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ENGINEERING AND GEOMETRIC CONSTRAINTS
OF A SIX DEGREE OF FREEDOM SYNERGISTIC
PLATFORM MOTION SYSTEM

By
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May 1977

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AIR FORCE SYSTEMS COMMAND
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Recent controversy surrounding the training effectiveness of the six degree of freedom, synergistic platform motion system is centered on several issues, one of which is, surprisingly, just exactly what motion the platform is capable of producing. This paper presents the primary equations and constraints, as well as a number of derived constraints applicable to the Advanced Simulator for Pilot Training (ASPT), a representative motion system.

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PREFACE

This technical report grew out of a short briefing on the same topic. The equation derivations were conducted in support of project 1123, task 112303. Dr. Milton Wood, Project Scientist; Mr. Warren Richeson, Task Monitor; and Mr. Michael L. Cyrus, Principal Investigator. This work was conducted at the Flying Training Division of the Air Force Human Resources Laboratory.

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I. INTRODUCTION

The Advanced Simulator for Pilot Training (ASPT) is located at Williams Air Force Base, Arizona. ASPT is a research simulator under the operational command of the Flying Training Division, Air Force Human Resources Laboratory (AFHRL), Williams AFB, Arizona. The analysis presented in this paper is based on the characteristics of the Link, 60-inch, 6-post motion system which is part of the ASPT. The ASPT motion system is characteristic, in terms of its excursion capability, of off-the-shelf simulators available today.

II. MOTION SYSTEM RESTRICTIONS

Normally, we think of motion as composed of two elements – intensity and phase. Intensity is composed of the amplitude and time duration of a particular motion, while phase essentially refers to the lag between commanded inputs and resulting outputs. It is motion intensity with which this paper is primarily concerned, since phase is easily controlled on modern simulation systems through the use of highly responsive servo systems driven by sufficient computational power.

In the area of motion intensity, there are three primary equations:

$$C_1 = R + DP_i - B_i \qquad i = 1, 2, 3, 4, 5, 6 \qquad (1)$$

$$C_{min} \leqslant ||C_i|| \leqslant C_{max} \qquad i = 1, 2, 3, 4, 5, 6 \qquad (2)$$

$$\dot{C}_{min} \leqslant \frac{d}{dt}||C_i|| \leqslant \dot{C}_{max} \qquad i = 1, 2, 3, 4, 5, 6 \qquad (3)$$

Expressed verbally, the first represents the geometrical relationship between cylinders (C_i), platform controid (R), platform orientation (D), and the platform and base leg attach points (P_i and B_i, respectively). This equation is the one which relates the servo system performance to the overall motion system performance. Equation 2 simply states the restrictions on the cylinder extension from fully retracted ($\dot{C}_{min}$) to fully extended ($\dot{C}_{max}$). The "60 inch" nomenclature used with respect to the ASPT 6-post system refers to the fact that $C_{max} - C_{min} = 60$ inches. Equation 3 represents the limitations on the rate of cylinder movement which is a function of several variables including the servo system, hydraulic pressure, platform payload and the like. For ASPT cylinder velocity lmits of approximately ± 19 inches/sec are applicable, $C_{min} = 103''$, and $C_{max} = 163''$ (Martin & Kron, 1974). Newer motion systems have much improved cylinder response characteristics, although their geometric properties remain similar to ASPT.

The only additional information required to completely derive all possible motion system relationships is the placement of the base leg and platform attach point vectors in their respective planes of reference.

The inertial frame of reference is a right-handed coordinate system with origin on the floor, Z-axis pointed into the earth, and X-axis pointed along the nose-tail line of the simulated aircraft when it is in the fully retracted (motion off) position. At this time, the platform center of gravity is directly over the origin. The platform reference is a right-handed reference plane with the X-axis out the nose of the simulated aircraft and the Y-axis out the right wing. With this convention, and assumption that angles are measured positive from X to Y, then the base leg vectors are as presented in Figure 1.

Leg #	1	2	3	4	5	6
Coordinate						
X	59.13844	59.13844	37.9808	−97.1192	−97.1192	37.9808
Y	78	−78	−90.2154	−12.2154	12.2154	90.2154
Z	0	0	0	0	0	0

Figure 1. **Base leg vectors in inches (inertial frame).**

Likewise, the platform attach point vectors are stated in Figure 2.

Leg #	1	2	3	4	5	6
Coordinate						
X	83.1384	83.1384	−38.9711	−44.1673	−44.1673	−38.9711
Y	3.0	−3.0	−73.5	−70.5	70.5	73.5
Z	0	0	0	0	0	0

Figure 2. **Platform attach point vectors in inches (Platform reference system).**

Each base leg has a fixed length of 97.8844 inches, while the platform attach point vectors all have a fixed length of 83.1925 inches. The difference, together with the floor and platform placement of these vectors, provide the geometrical advantage for each degree of freedom (Martin & Krown, 1974).

Derived Relationships

Returning to Equation 1 we see that

$\dot{C}_i = \dot{R} + \dot{D}P_i$ (The representations for D and $\dot{D}$ are given in Appendix A) (4)

This equation is the one which is used to determine single axis velocity relationships. Although such relationships vary with platform position and orientation, normally either the neutral position, or the best case (maximum geometric advantage), is used. Contractors, in particular, use this latter category. Representative single dimension position and velocity limits of ASPT are shown in Figure 3.

Description	Variable	Position Limits	Velocity Limits
Fore – Aft	X	−41″ to +51″	±33″/Sec
Left-Right	Y	−41″ to +41″	±34″/Sec
Up-Down	Z	−32″ to +36″	±24″/Sec
Roll	ϕ	−25° to +25°	±19°/Sec
Pitch	θ	−24° to +23°	±17°/Sec
Yaw	ψ	−31° to +31°	±23°/Sec

Figure 3. **Single degree of freedom limits.**

Several comments on Figure 3 are appropriate at this point. First, the motion system is dually constrained by geometric (position) and engineering (velocity). Improved servotechnology will increase the velocity limits; however, position constraints will remain fixed. Additionally, the ASPT geometry is configured so that the most capable degrees of freedom are X, Y, and ψ: precisely, those most useful for a transport-like device, whereas ϕ, θ, and Z are more constrained. Finally, these charts tend to make the reader believe that the platform can simultaneously move throughout any combination of these single degree of freedom limits. Actually, the synergistic property of the motion system implies that it takes the combined motion of all six legs to produce motions along any single degree of freedom, such as heave (Z). The interactive nature of such motion is clear: if the platform heaves, say, 24 inches, then its capability to roll is drastically reduced. This property makes proper motion cue coordination difficult in many cases, and impossible in others. Several researchers have conducted extensive analysis to determine the optimum trade-off between cues for display purposes (Parrish, Dieudonne, Bowles, & Martin, 1973).

In all cases, platform motion may be divided into three categories: motion due to cueing, velocity washout motion, and position washout motion. By cueing we mean the motion of the platform commanded to represent some force, rotational velocity, or vibration effort. By velocity washout we mean the motion of the platform commanded to keep the platform from running into the hardware stops, that is, running out of room. By "position washout" we mean the motion of the platform commanded to return it to a neutral position ready to display another cue. This analysis ignores the many gravity align techniques which attempt to tilt the platform in such a way as to induce the feeling of external force. At the present time there is considerable controversy in the simulation community over exactly what constitutes motion cueing. One of the most ambitious research efforts being conducted with AFHRL currently is the Pilot Sensory Modelling approach. This approach could eventually lead to better motion driving algorithms. Present motion cues are divided into three categories:

1. Disturbance cues such as occur in stall, rough air, runway rumble, speed brake buffet, engine out, touchdown, etc.
2. Acceleration cues, primarily along the translational axis (X, Y, Z)
3. Velocity cues, primarily for rotational cueing (ϕ, θ, ψ).

For analysis purposes, we will assume that an acceleration drive is used for translational cueing, and a velocity drive is used for rotational cueing.

III. ACCELERATION CUE CAPABILITY

Normally, the analysis of acceleration cues is carried out independently along each axis (X, Y, Z). Acceleration cues are the most difficult to maintain since their use of the available space is rapid. There are three effective constraints on acceleration cues: the position constraint, the maximum velocity constraint, and a time of cue display constraint induced by effective washout rate. Washout rates are generally chosen from .01g to .08g. This rate is considered subliminal. Evaluation of cue intensity is likewise difficult. Cue (acceleration) sensing is generally thought to be a function of the product of acceleration and the time duration for "small" accelerations and times. Thus .1g for .2 seconds is roughly equivalent to .2g's for .1 second. Therefore, it suffices to examine the capability of the motion platform to impart accelerations for the longest time period prior to washout. Figure 4 represents the scheme we will examine. The "bang-bang" washout scheme is the most efficient one possible from the viewpoint of maximizing cue duration for a fixed maximum washout level. (We will omit the derivation, from the Hamiltonian, of the variational solution to this problem. The basic theory of bang-bang controllers can be found in most texts on optimal control.) (Athans & Falb, 1966; Kirk, 1970).

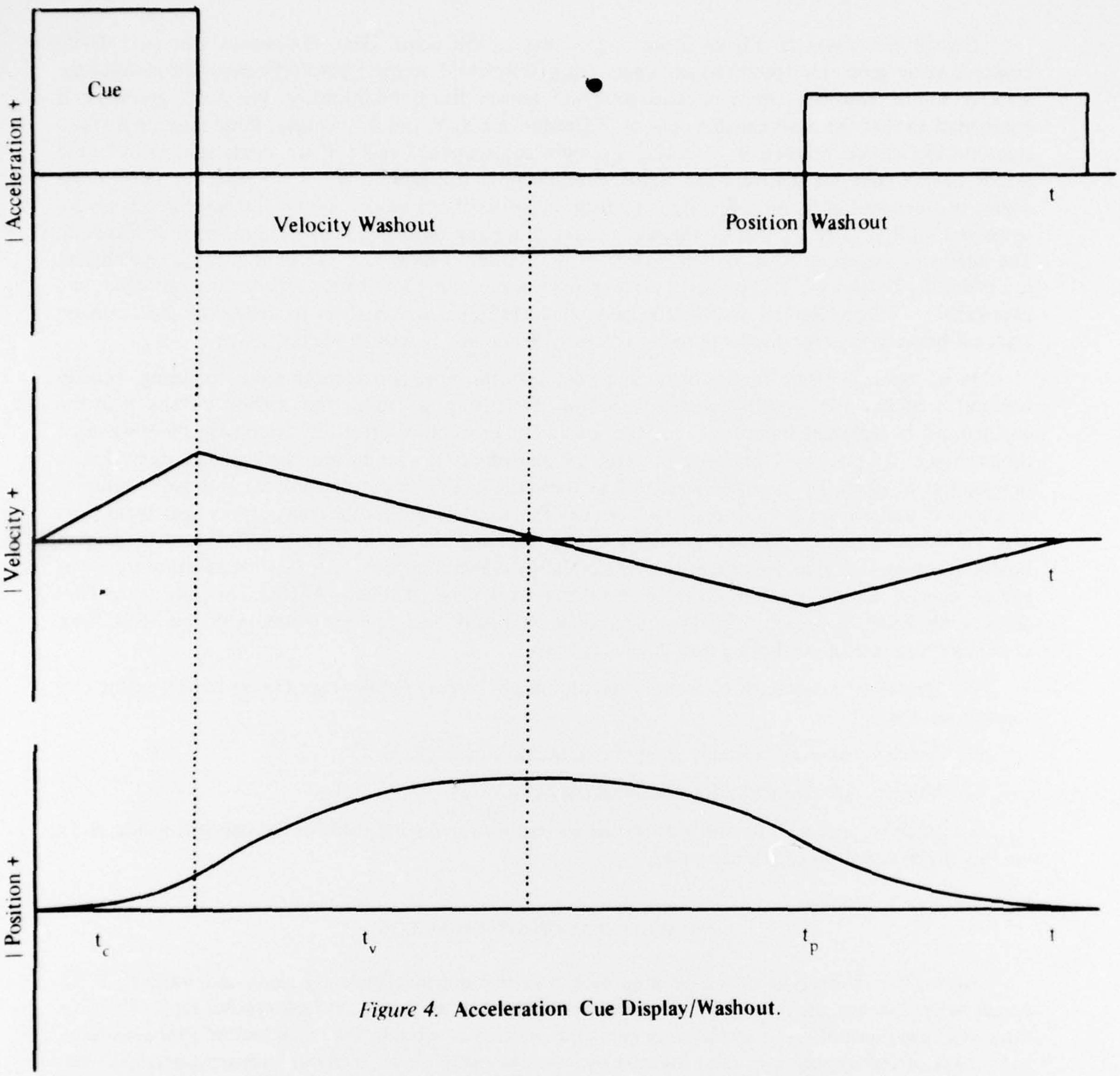

Figure 4. **Acceleration Cue Display/Washout.**

If we let

a_c be the cue acceleration, in g's.

t_e be the cue duration, in seconds.

θ be the washout acceleration level, in g's.

t_v be the velocity washout duration, in seconds

t_p be the position washout duration, in seconds

With these assumptions, we have two constraints:

$$V \leqslant V_{max} \text{ where } V = a_c t_c \tag{5}$$

$$P + \frac{V^2}{2\theta} \leqslant P_{max} \text{ where } P = \frac{a_c t^2_c}{2} \tag{6}$$

Implicit in the previous constraint equations is the additonal assumption we have started platform movement in a single degree of freedom (X, Y, Z) from rest. The V_{max} and P_{max} terms are the corresponding limits taken from Figure 3. At this point, we introduce the variable, α, which represents the ratio of cue height to washout height:

$$\alpha = \frac{a_c}{\theta} \quad \text{where } \alpha \geqslant 1 \tag{7}$$

With this convention we have:

$$V = \alpha\theta t_c \leqslant v_{max} \tag{8}$$

$$P + \frac{V^2}{2\theta} = \frac{[\alpha\theta + \alpha^2\theta]}{2} t^2{}_c \leqslant P_{max} \tag{9}$$

The maximum cue presentation time t_c is

$$t_c = \min \left\{ \frac{V_{max}}{\alpha\theta}, \sqrt{\frac{2P_{max}}{\alpha(\alpha+1)\theta}} \right\} \tag{10}$$

The first constraint corresponds to the velocity (or engineering constraint); the latter, to a geometric constrain. It is desirable to know what is the trade-off between the two constraints; i.e., which is more constraining. If it is servosystem technology, then by improving our servos, we can improve platform motion intensity. The question may be phrased, which capability do we run out of first, the velocity required to support increased acceleration, or the room to display that acceleration? Ideally, a motion system would be well designed from this criterion if the maximum capability of the simulator geometry is available for use, without being overdesigned in terms of excess velocity capability.

Whatever the time length of the cue presented, the relative washout time durations are functions of the cue time duration:

$$t_v = \alpha t_c \tag{11}$$

$$t_p = \sqrt{2\alpha(\alpha+1)} \; t_c \tag{12}$$

And since the cue delivered is presumably always above sensory threshold ($\alpha \geqslant 1$), we have

$$\frac{t_c}{t_v + t_p} = \frac{1}{\alpha + \sqrt{2\alpha(\alpha+1)}} \tag{13}$$

which represents the ratio of cue display time to washout display time.

Equations 10 through 13 completely define the acceleration cueing regime a platform motion system is capable of supporting outside gravity align techniques, whose purpose is to rotate the cockpit subliminally in such a way as to induce the feeling of long-term X and Y forces. Cue duration (Equation 10) is seen to be a function of four variables: effective washout threshold (θ), position (P_{max}) and velocity

(V_{max}) constraints, and the ratios of delivered acceleration to washout accelerations (α). Equations 11 through 13 completely define the optimum (fastest) washout time durations as a function of α and the original cue duration.

In the foregoing analysis no mention was made of the effect of the oscillatory nature of aircraft accelerations. This action was deliberate for two reasons: (a) aircraft accelerations are, except for vibration and buffet effects, too long-term to be simulated even with large scale factors for most maneuvers; (b) drive schemes differ radically in their method of handling washout, gravity align and the like. This method of presentation is thought to be general in its application.

IV. VELOCITY CUEING CAPABILITY

Unfortunately, no simple analysis tool exists for examining the rotational degrees of freedom, as is the case for translational degrees of freedom. Various theories exist for delivering rotational cues; the most popular among pilots is the velocity cueing drive. This drive attempts to maximize, within a variety of constraints, the mathematical correlation between simulator platform rotational motion and simulated aircraft rotational motion. Basic research has not provided, to this date, a clearcut answer to the question of "optimum" motion drive algorithms. Some of the difficult involved in the development rotational cueing algorithms is due to the combination of low rotational acceleration and velocity thresholds, together with very long adaptation times (Gum, 1972). On ASPT, the relative threshold values for rotational cueing are $.5°/sec^2$ and $1.5°/sec$, respectively, for acceleration and velocity. Adaptation times normally range from 20 to 30 seconds. It is not feasible to use a level of washout this low for rotational cueing since it would be impossible to keep the subject from noticing the sensation of excessive tilt. Further, limiting the washout rate in a manner similar to the translational cueing would result in a very low rotational cueing. Conversly, high washout rates axiomatically imply "negative" or "reverse" cueing. That is, the sensation of moving the wrong way relative to the simulated aircraft motion. Instead, a trade-off between the two extremes is used, necessarily containing both positive and negative cueing aspects. In Figure 3, it is seen that rotational cueing lasts from approximately 1.3 to 1.5 seconds up to 15 to 20 seconds, depending upon whether exclusive use of the channel (roll, pitch, or yaw) is available, the average velocity required, and a variety of other constraints imposed by the software. For typical contact maneuvers in ASPT (loop, aileron roll, etc.) wherein multiple channel (degree of freedom) use is demanded, virtually all cues except gravity align, normally terminate in less than one second. That is, the excursion demands placed upon the motion platform will force it into a position washout situation in under a second. (Velocity washout, whatever its form, is assumed complete at that time.) It is possible to adjust a motion system to be more "responsive" (and thus cut the "onset" cue time) or less responsive (and lengthen that time). The final choices made are invariably based on a combination of engineering and subjective data, and will remain so until basic research into the human motion sensory mechanisms establishes and validates a mathematical model the engineer can use to design better motion algorithms.

V. SUMMARY

The key elements of this paper are as follows:

1. ASPT-type motion system response is constrained by the geometric design and hardware implementation. Newer systems (post-1973) are constrained primarily by their physical (geometric) limitations.

2. ASPT-type motion systems are not capable of reproducing aircraft motion accurately. This fact is deducible purely from geometric considerations, namely equations 1 and 2 together with Figure 1 and 2, and the knowledge of the aircraft motion being simulated.

3. ASPT-type motion systems possess most of their motion response capability in the X, Y, and yaw dimensions, precisely those most compatible with transport-like aircraft, as opposed to fighter-type aircraft. Further, the roll, pitch and z degrees of freedom interact more heavily than the X, Y, and yaw degrees of freedom.

At the same time, a motion system, even though it cannot provide realistic motion in an engineering sense, may still prossess considerable training value. That value must be determined through actual training research.

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APPENDIX A: ASPT DIRECTION COSINE RELATIONS

The ASPT platform to inertial direction cosines are:

$$
D = \begin{bmatrix}
\cos\theta \cos\psi & \cos\theta \sin\psi & -\sin\theta \\
\begin{array}{l}\sin\phi \sin\theta \cos\psi \\ \quad -\sin\psi \cos\theta\end{array} & \begin{array}{l}\sin\phi \sin\theta \sin\psi \\ \quad +\cos\psi \cos\phi\end{array} & \sin\phi \cos\theta \\
\begin{array}{l}\cos\phi \cos\psi \sin\theta \\ \quad +\sin\psi \sin\phi\end{array} & \begin{array}{l}\cos\phi \sin\psi \sin\theta \\ \quad -\sin\phi \cos\psi\end{array} & \cos\phi \cos\theta
\end{bmatrix}
$$

The derivative, D, is composed of three parts,

$$
\dot{D} = \dot{\theta} \begin{bmatrix}
-\sin\theta \cos\psi & -\sin\theta \sin\psi & -\cos\theta \\
\sin\phi \cos\theta \cos\psi & \sin\phi \cos\theta \sin\psi & -\sin\phi \sin\theta \\
\cos\phi \cos\psi \cos\theta & \cos\phi \sin\psi \cos\theta & -\cos\phi \sin\theta
\end{bmatrix}
$$

$$
+ \dot{\phi} \begin{bmatrix}
0 & 0 & 0 \\
\begin{array}{l}\cos\phi \sin\theta \cos\psi \\ \quad +\sin\psi \sin\phi\end{array} & \begin{array}{l}\cos\phi \sin\theta \sin\psi \\ \quad -\cos\psi \cos\phi\end{array} & \cos\phi \cos\theta \\
\begin{array}{l}-\sin\phi \cos\psi \sin\theta \\ \quad +\sin\psi \cos\phi\end{array} & \begin{array}{l}-\sin\phi \sin\psi \sin\theta \\ \quad -\cos\phi \cos\psi\end{array} & -\sin\phi \cos\theta
\end{bmatrix}
$$

$$
+ \dot{\psi} \begin{bmatrix}
-\cos\theta \sin\psi & \cos\theta \cos\psi & 0 \\
-\sin\phi \sin\theta \sin\psi & \begin{array}{l}\sin\phi \sin\theta \cos\psi \\ \quad -\sin\psi \cos\phi\end{array} & 0 \\
\begin{array}{l}-\cos\phi \sin\psi \sin\theta \\ \quad +\cos\psi \sin\phi\end{array} & \begin{array}{l}\cos\phi \cos\psi \sin\theta \\ \quad +\sin\phi \sin\psi\end{array} & 0
\end{bmatrix}
$$

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